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RATIONAL ELECTROTHERMAL CONDITIONS FOR OPERATION OF LANTHANUM CHROMITE ELECTRIC HEATERS

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A calculation of temperature fields is given for solid and tubular lanthanum chromite electric heaters. A triple diagram of "heater temperature – furnace temperature – specific surface power" is developed for heaters of generally employed sizes in the range of 1000 – 2000°C.

Lanthanum chromite electric heaters are used in resistive furnaces for production, treatment, and testing of articles made of ceramics, glass, composites, and high-melting metals. In oxidizing and neutral media these heaters provide long-term stable service at temperatures up to 1800°C (USSR Inv. Certif. No. 132347) [1 – 3]. Lanthanum chromite heaters are regarded not only as a source of higher temperatures in the furnace but also as a replacement for silicon carbide heaters in the most common furnaces with temperatures not more than 1450°C, which would provide manifold extension of the furnace service life [3]. An evident advantage of lanthanum chromite heaters is their high specific resistance, making it possible to use them in the form of elements with a large diameter (lateral cross section) and, at the same time, not to exceed the generally accepted admissible current strength in the electric circuit.

Knowledge of the temperature field inside the heater body is necessary for heater design (choice of shape, diameter, wall thickness) and for developing rational electrothermal conditions (temperature of the furnace and the heater radiating surface, thermal load, i.e., specific surface power). Although temperature-field calculations have been performed for ceramic heaters [4 – 6], they were not used to determine rational thermal conditions for heater operation. Existing plots of specific surface power – furnace temperature – heater temperature were calculated accounting for just the temperature on the heater surface without regarding the temperature inside the heater [7]. The maximum permissible thermal load is determined from the maximum permissible temperature just on the heater surface $t_{\text{h, max}}$. However, since the thermal conductivity of lanthanum chromite is low (within the temperature interval of 900 – 1800°C it is around 2 W/(m · K) [3]), the actual maximum temperature inside the heater body is significantly higher than $t_{\text{h, max}}$. Therefore, there is a risk of exceeding the temperature limit of the physicochemical stability of lanthanum chromite t_{lim}, which, considering the intense incongruent high-temperature evaporation of lanthanum chromite and the likely formation of an $LaCrO_3 - La_2O_3$ eutectic, should be taken equal to 2000°C [8].

We consider the thermal conditions of a heater operating in a stationary mode, which is normally used for the calculation of heaters in high-temperature resistive electric furnaces [9]. The Joule heat emitted by a heater of volume V in a stationary mode is fully transmitted into the ambient space via its outer surface F (here and elsewhere the active radiating part of the heater is meant):

$$qV = WF,$$

where q and W are the heat emission per unit volume of the heater and its specific surface power.

For a solid cylinder and a tube, respectively,

$$q\pi R^2 l = W 2\pi Rl; \tag{1}$$

$$q\pi l (R^2 - r^2) = W 2\pi Rl, \tag{2}$$

where l, R, and r are the length and the outer and inner radii of the heater, respectively.

Assuming the current density to be equal across the cross section of the electric heater [10], we use the equation of the temperature curve inside a body with uniformly distributed internal heat sources [11]:

for a solid cylinder

$$t = t_{\text{h}} + \frac{qR^2}{4\lambda}[1 - (r_x/R)^2];$$

for a tube

$$t = t_{\text{h}} + \frac{qR^2}{4\lambda}[1 + (r_x/R)^2 2\ln(r_x/R) - (r_x/R)^2],$$

where t_{h} is the temperature of the heater outer surface; λ is the heater thermal conductivity; r_x is the running radius in the heater width.

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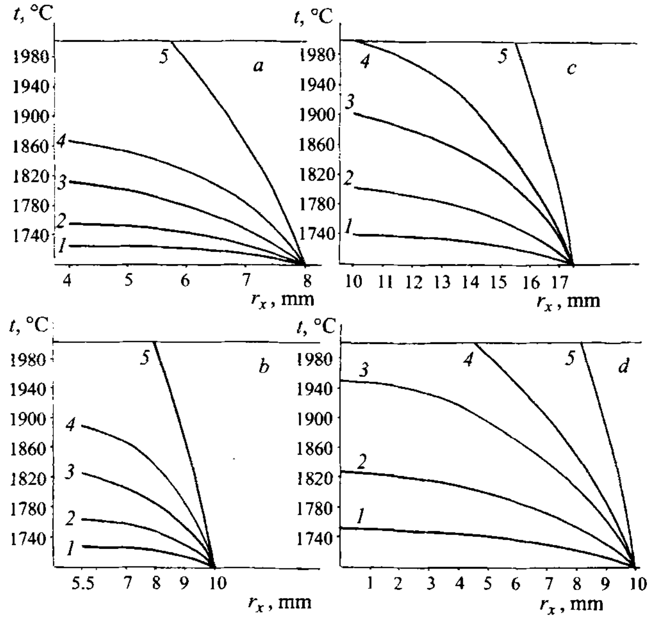

Fig. 1. Temperature fields of lanthanum chromite heaters with diameters of: *a*) outer $D = 16$ mm and inner $d = 8$ mm; *b*) $D = 20$ mm and $d = 11$ mm; *c*) $D = 35$ mm and $d = 20$ mm; *d*) $D = 20$ mm; *1*, *2*, *3*, *4*, and *5*) specific surface power 2, 5, 10, 15, and 35 W/cm^2, respectively.

Here λ is considered to be a constant, which is quite admissible in our case for a narrow interval of high temperatures [10]. After transformation using expressions (1) and (2) we obtain:

for a solid cylinder

$$t = t_h + \frac{WR}{4\lambda}[1 - (r_x/R)^2];$$

for a tube

$$t = t_h + \frac{WR}{2\lambda(R^2 - r^2)}[R^2 - r_x^2 + 2r^2 \ln(r_x/R)].$$

Results of a calculation of temperature fields in industrially produced solid and tubular lanthanum chromite electric heaters [12] are shown in Fig. 1. Direct temperature measurements using a pyrometer with a vanishing thread confirmed the calculated data. In particular, for a specific surface power of 12 W/cm^2 and a surface temperature of 1700°C for a solid heater 20 mm in diameter, the highest temperature inside the heater was 1950°C, and for a tubular heater 20 mm of outer diameter and 11 mm inner diameter that temperature was 1840°C. The temperature field of a functioning heater obviously creates prerequisites for the zonality of transformations (wear) of the heater material in service. For example, the evaporation rate of lanthanum chromite in layers with higher temperatures can be higher than in surface layers. On the other hand, although more gaseous products are formed in the depth of the heater, their release via pores is hindered compared to the outer surface.

Data on temperature fields make it possible to develop nomograms of rational combinations of the furnace temperature and the specific surface power for lanthanum chromite electric heaters of the most generally employed sizes. The admissible temperature t_{lim} should be taken equal to 2000°C. Data on the temperature differences inside the heater are useful in relation to the physicochemical stability at a specified service temperature and to possible thermal stresses and shocks experienced in thermal cycles.

Complex heat exchange occurs during heater operation: in addition to the main quantity of heat released by radiation, a certain part of the power is released by contact with the ambient medium, mostly by convection. Calculations show that at a temperature of 1400 – 1800°C, heat release by convection in calm air for heaters with an outer diameter of 20 – 25 mm does not exceed 3%, and its role can be neglected [13]. Therefore, in a calculation of the specific surface power of a heater, it is correct to limit oneself to the heat radiation equation:

$$W = \varepsilon_h C_0 [T_h^4 - T_f^4],$$

where ε_h is the relative radiating capacity; C_0 is the radiation constant of an absolutely black body; T_h and T_f are the absolute temperatures of the heater surface and the furnace space.

In heat transfer in a furnace the specific surface power of the heater is determined by the expression [7]

$$W = C_{\mathrm{red}} [T_h^4 - T_f^4], \tag{3}$$

where C_{red} is the reduced coefficient of radiation of the system:

$$C_{\mathrm{red}} = C_0/[1/\varepsilon_h + F_h/F_f(1/\varepsilon_f - 1)], \tag{4}$$

where ε_h and ε_f are the relative radiating capacities of the heater and the furnace lining material; F_h and F_f are the surface areas of the heater and the furnace.

Since in most cases $F_f \gg F_h$, then $C_{\mathrm{red}} = \varepsilon_h C_0$.

In a calculation of the actual specific surface power of a heater it is necessary to take into account the relationship of W and C_{red}, the mutual position of the heaters, and the effect of the size of the articles. For this purpose, corrections in the form of appropriate coefficients are introduced [14]. In a calculation for batch-type furnaces and holding zones of continuous furnaces, the actual surface power of the heater is

$$W_a = W\alpha_h \alpha_c \alpha_{\mathrm{ef}}, \tag{5}$$

where α_h is the step coefficient; α_c is a factor taking into account the relationship $W = f(C_{\mathrm{red}})$; α_{ef} is the coefficient of heater radiation efficiency; for rod heaters it is taken equal to 0.68.

The correction coefficient α_h in the calculation is taken equal to 1.05 for a distance between the axes of the heaters equal to three heater diameters $3D$. The relative radiating capacity of a heater is taken equal to 0.9 [15].

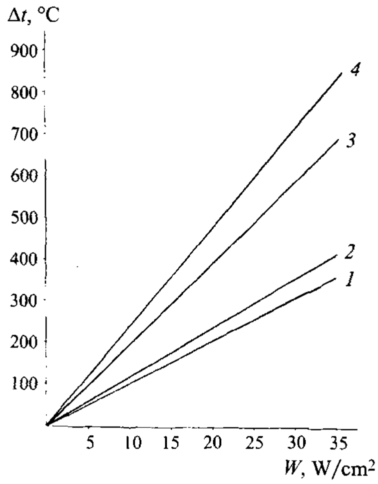

Fig. 2. Maximum temperature difference in lanthanum chromite heaters with diameters of: *1*) outer $D = 16$ mm and inner $d = 8$ mm; *2*) $D = 20$ mm and $d = 11$ mm; *3*) $D = 35$ mm and $d = 20$ mm; *4*) $D = 20$ mm.

In determining the region of admissible values of the surface power of heaters, one should take into account the temperature difference inside the heater. The maximum temperature difference will be:

for a solid cylindrical heater

$$\Delta t = t_{ax} - t_h = \frac{WR}{2\lambda}, \quad (6)$$

for a tubular heater

$$\Delta t = t_{in} - t_h = \frac{WR}{2\lambda(R^2 - r^2)}[(R^2 - r^2) - 2r^2 \ln(R/r)], \quad (7)$$

where t_{ax} is the longitudinal-axis temperature; t_{in} is the inner-wall temperature.

Plots of maximum temperature difference versus specific surface power obtained from Eqs. (6) and (7) for heaters of the most generally employed sizes are shown in Fig. 2.

Equations (3) – (5) were used to plot a triple diagram of heater temperature – furnace temperature – specific surface power (Fig. 3) in the temperature range of 1000 – 2000°C for lanthanum chromite heaters. Taking into account the maximum temperature difference and the inadmissibility of exceeding a temperature of 2000°C, curves of maximum admissible values of the specific surface power for heaters of the considered sizes are plotted on the diagram. These curves delimit the regions of admissible thermal loads of the heaters for different temperatures of the furnace.

However, the temperature difference inside the heater body results in thermal stresses, which are a decisive factor determining heater stability in service. Therefore, rational electrothermal conditions for heater operation should be below the maximum admissible values of the specific surface power, which will provide heightened reliability and longevity of the heater.

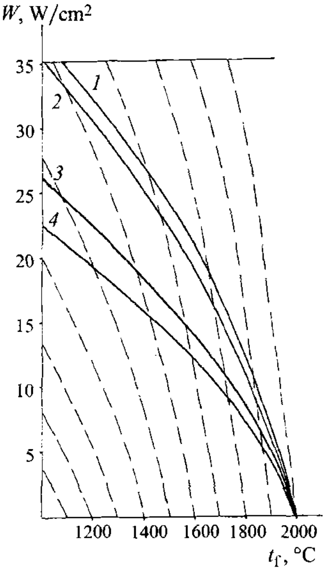

Fig. 3. Diagram of the specific surface power in lanthanum chromite heaters: the solid curves correspond to the maximum admissible values of the specific surface power for heaters with diameters of: *1*) outer $D = 16$ mm and inner $d = 8$ mm; *2*) $D = 20$ mm and $d = 11$ mm; *3*) $D = 35$ mm and $d = 20$ mm; *4*) $D = 20$ mm.

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